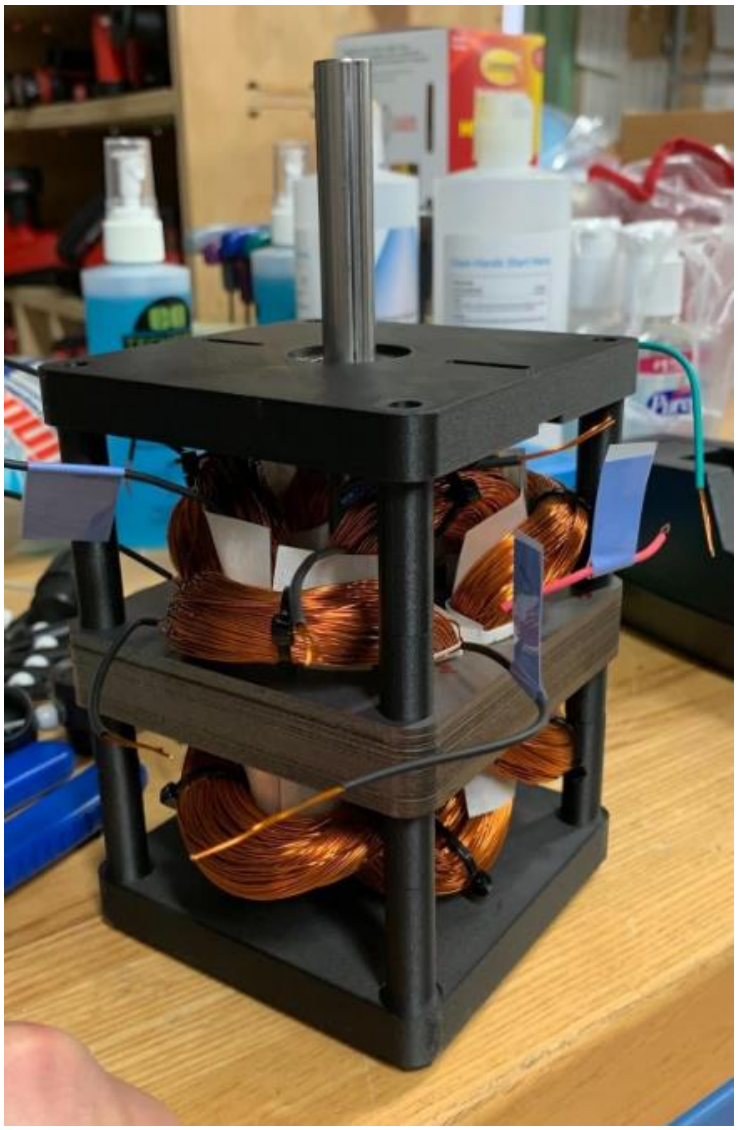
Compact Low Voltage Asynchronous Induction Motor Commissioned by Grainger Teaching Studio



S. Gerbers, J. Keller, A. Chan, N. Seibold
Department of Mechanical Engineering
University of Wisconsin - Madison
27 April 2021

Executive Summary

With very few accessible hands-on experiences relating to power conversion being offered at the University of Wisconsin – Madison, our team has been tasked by the Grainger Teaching Studio with building asynchronous induction motor prototypes to be replicated and optimized as in-class projects. The broad objective for this project was to have a spinning induction motor by May 2021. There are many stakeholders involved in the outcome of the project, including the instructional staff, the client commissioning the project, and the prospective students participating in the hands-on learning. Each group presents objectives that must be considered in the planning and undertaking of this project. Designs must also be simple for the students in the classroom.

Extensive research into current designs of induction machines has been conducted and yielded a sufficient level of knowledge regarding the operations of induction machines (summarized in this report) to fabricate a prototype. With arguments in favor of this project including enhanced hands-on learning, logistical ease for professors, and the potential for reducing carbon emissions, it is clear to see that commissioning this project is more than justifiable.

The first motor design was modeled using SolidWorks. All key components were included to ensure that the pieces properly fit together, and that the design was robust. Equations and tolerancing were implemented, allowing for easy modification of the assembly. Materials were included to meet the client needs and make the model more representative of what the final motor will look like. Design features were chosen based on the client's needs, cost, and manufacturability. A reference DC motor provided by the Grainger Teaching Studio also aided in the development of the first design. This assembly served as a baseline for future prototypes.

The primary goal of the first prototype was simply for it to spin; performance of the motor itself was not a key indicator of project success. However, the team still had to make decisions regarding cost, geometry, manufacturability, and other factors. Each motor design is allowed a sum of $100 to manufacture. This includes costs for all parts – housing plates, wire, laminations, end plates and others. A large portion of the motor was able to be fabricated in house, which was favored by the client. The first prototype met that goal, finishing at an approximate unit price of $90 per motor, including both in-house and purchased parts. Decisions were also made regarding the geometry. A squirrel cage rotor was chosen for simplicity with copper bars going through the rotor laminations to create a shorted circuit in the rotor. In future designs, a skewed rotor design may be implemented for better performance, and copper wires may replace the copper bars to lower costs and increase manufacturability. Manufacturability was emphasized continuously and was a key factor in every design decision made. A more complicated design may be tough for students to piece together or learn from. Keeping the design simple is advantageous for all stakeholders impacted by the project.

The first prototype was completed in mid-April and passed a hi-pot and phase resistance test. The motor spun, indicating that the first prototype was a success. A review was conducted with the client outlining the progress of the project, and future considerations were discussed in effort to maximize student potential learning. The project remains on schedule, and the second prototype is currently being designed. Material selection, geometry, cost minimization, and manufacturability all remain top priorities going forward.

Table of Contents

Introduction

Do you lack the confidence going into a professional engineer career solely because you do not understand how things are physically assembled and interact in the real world? Young engineers today are often lacking in confidence due to not being exposed to real-world, hands-on learning. This pivotal component is often left out in academic settings, leaving students on their own with little more than the textbook knowledge they have retained. The Grainger Teaching Studio aims to provide students this opportunity through the fabrication and optimization of an asynchronous induction motor in a structured, guided format. Induction motors are one of the leading machines in electrical power consumption applications. The AC motors will be based on an existing DC motor design currently used in the Grainger Lab. AC motors are known to have a much higher efficiency and are more commonly used in favor of DC motors in today's industry.

There are numerous ways induction motors can be fabricated, but they often must be modified to create a desired output, such as a torque or speed, for a given application. The optimization process may require a change in the magnetic field generated, a material change, among many others. While the machines created for the client will be on a smaller scale than typically used in industry, the key learning objectives from the course will certainly be applicable to larger induction machines students may see in the workplace. Software will be used to simulate the behavior of the machine and see how the motor performance is altered when parameters are changed. The prototypes will be provided alongside a detailed fabrication manual to assist students as they begin their optimization process.

There are many stakeholders that are involved in this project, including the professors, client and students. Research has also been conducted on the motors. The Grainger Teaching Studio has provided a DC motor to serve as an example for the project. In addition, similar projects and solutions were looked in to in preparation for the AC motor design and fabrication process. Design decisions were made based among client needs, manufacturability, cost, and others. Upon iterating the first prototype design, the first motor design was modeled using SolidWorks. Parts were ordered and the fabrication process began. A couple design issues were encountered, noted, fixed and implemented into the final working prototype. The last step in the process was to test the prototype using three tests specified by the client. These tests were completed, and the entire process was reviewed with the client. Feedback and future considerations involving manufacturability, design and cost were discussed in preparation for future prototypes.

Problem Statement

Engineering student graduate college with an abundance of technical knowledge, but they often lack the hands-on experience that may enhance their skillset in preparation for an increasingly competitive industry. The Grainger Teaching Studio aims to provide students within the Electrical and Computer Engineering department this opportunity through the fabrication an AC induction motor. A research study conducted at the University of Colorado at Boulder found that students who opted to take a hands-on structured engineering course in favor of an equivalent non-hands-on course had an average of a 19% higher gain in retention rates [1]. This high-level course would challenge students to optimize machine parameters, which include, but are not limited to, the number of poles, number of winding turns, or a desired torque. We intend to provide the lab with 3 to 5 prototypes for student reference that are inexpensive for classroom use. After speaking with the client, his main concern was the time commitment on behalf of the teaching staff. Simple designs and a detailed fabrication instruction manual will mitigate the hassle that many professors associate with hands-on projects. With variable parameters, the manual will also provide students the tools necessary to create their own optimized designs. The prototypes will allow students in this high-level course the opportunity to round out their college education and gain a competitive edge going into the industry.

Stakeholders

This project is revolved around education, requiring a multitude of stakeholders to buy into and embrace the project, which is unlike an industrial project where certain goals and parameters must be met. To accomplish this, the thought process and needs of the primary stakeholders (professors, client, and students) have been outlined below with a corresponding list of specific tasks to ensure the accomplishment of the overarching goal of this project outlined in the problem statement above.

Professors

While the main end user will be the students, the project design must be versatile and effective enough to be added to the professor's curriculum, else the students' needs are made moot. Therefore, in a prioritized list from most to least important below, a few key points are outlined to ensure that this project is viable enough for professors to incorporate into a class:

- Fabrication Instructional Manual
- Easily Configurable and Adaptable Parameters

The primary objective in eliminating hassle for professors is having an easily accessible and robust fabrication manual. The manual is written with the intent that a professor of a class with no fabrication experience could teach the class. The fabrication manual will include no theory regarding the workings of windings, stators, cages, etc. that is not directly tied to fabrication. Not only would this material be repetitive as the assembly will be required alongside course readings detailing the theory behind induction motors, but it would also limit the adaptability of the project, binding it to the depth of content covered. For example, if an ECE 377 level knowledge of magnetism and induction is assumed and written in the manual, the manual would be intimidating at best and all together discarded if the machine were desired to be used in an introduction to electrical engineering class.

The second priority for professors is that the motors must be easily configurable and have adaptable parameters. As mentioned before, this project is meant to be useful and engaging regardless of what level of class it is used in. While a lower-level class may be satisfied with simply building the motor and watching it spin, a graduate class may desire more. As a result, several parameters are left available for optimization incorporation opportunities. A few of these potential parameters include altering the number of poles, windings, or wire gauge to exhibit how the manipulation of these parameters will lead to a change in the maximum torque output, start-up torque, efficiency, cogging, etc. By writing detailed opportunities for optimization, a professor can easily change the difficulty of the project depending on the education level and time commitment of students in the class, and students can have some sort of structure if trying to optimize their own design for the first time.

Client

The client for this project is Kyle Hanson, the WEMPEC Lab Manager at the University of Wisconsin – Madison. While he will not be directly impacted by the project as he is not the one who will be teaching or learning from the project, his reputation is on the line as he is the overseer of the project. All specifications and requirements he set as objectives are of the upmost importance. Most of the considerations for this stakeholder are taken up front during the planning and proposal portions of the design and therefore have already been set. The process of figuring out just what these objectives were required interpretation, clarification, and iteration. This process was documented in a design specification sheet as statements were taken from the client, interpreted by the team to come up with cold hard numbers, clarified to ensure quality, and finally thoroughly reassessed by both the client and the team multiple times in an iterative fashion to ensure that key objectives are the same before beginning prototyping. These specifications can be found in Table 1 below. It is important to note that all specifications outlined in this table are simply initial parameters and are open for further adaptation as the project goes on and the team encounters errors and opportunities that may shift the outcome objectives.

Table 1. Detailed design specifications derived from client needs.

Client Needs
Client Need Statement
The Grainger lab needs an induction machine design that can be easily manufactured so that students can take a class that provides hands on learning on induction machines.
Client Needs (in their words)
Needs a 3 phase AC induction motor that builds off of a previous project that involved a DC motor
Client is looking for an easy-to-build induction motor design that could be made by students
An instruction manual should accompany the design and be simple enough for average students with little hands-on experience
Motor should have 4 poles, operating at 1800 rpm
Single layer winding can be used for first design, but final design should utilize double layer winding
The design must be able to easily attach to an existing dino for torque testing and analysis
Design should be relatively inexpensive to produce
Spinning Prototype by end of semester
RFQ
Fabrication should be affordable for the student
Design should incorporate manufacturing techniques and materials found and provided by the Grainger Lab

Engineering Specifications					
Specification description	**Target**	**Unit**	**Test method**	**Rank**	**Met**
Materials					
Component materials stocked in the lab	All	-	Bill of materials with specified in-stock part, client evaluation	Nice	
1 48" x 10" metal sheet per motor	1	sheet	Solidworks metal surface area evaluation	Should	
Minimize fabrication costs	<100	$ ea.	Bill of materials with component costs, client evaluation	Should	
Specifications					
Coils/wiring should be identical, compatible with 3 phase AC supply, and assembled as designed	pass	-	Phase Resistance Test	Must	
Low torque to fit within dyno specs	<5	N*m	JMAG for pre-production / Dyno for post-production	Must	
Number of bars offset from number of slots	pass	-	Design Spec	Must	
Power specification	350	W	JMAG for pre-production / Dyno for post-production	Nice	
Wire Gauge	18-20	gauge	Design Spec	Should	
Squirrel Cage Rotor	pass	-	Client evaluation	Nice	
Overall Design					
Must fit on dyno c-face mounting bracket	pass	-	3D assembly modeling (pre-production) and trial testing (post-production)	Must	
4 poles	pass	-	Client Evaluation	Must	
Easy to manufacture with in-house equipment	pass	-	Client Evaluation	Must	
Skewed rotor to prevent cogging	pass	-	Client evaluation	Nice	
Operations & Deliverables					
Spinning prototype by end of semester	pass	-	Passes hi-pot and phase resistance tests, spins using specified voltage supply	Must	
Folder with all 3D models and manufacturing files	pass	-	Client Evaluation	Must	
Instruction Manual with optimization parameters and manufacturing techniques	pass	-	Client Evaluation	Must	

Students

The students will be the main stakeholder interfacing with the induction motor. By fulfilling the objectives to satisfy the client and professors involved, the students' needs will be met very easily with very little supplementary consideration. There is, however, one consideration of the upmost importance that is specifically related to the wellbeing of the student as they seek to navigate building their own induction motor from scratch. The aforementioned consideration is a simple and detailed fabrication process.

As mentioned in the professor stakeholder paragraph above, an instruction manual will be included to detail the fabrication process. Emphasis will be placed on considering the perspective of the students. This includes assuming minimal prior manufacturing experience and the need for step-by-step instructions. Although students inherently have some level common knowledge, this project could result in complex logic jumps and could lose many students' ability to learn along the way. This common issue in college level laboratory activities can be prevented by taking excessive notes during the prototyping stage that can be condensed and reviewed to craft the manual after a spinning prototype is finished. As this team is comprised of current undergraduate students, all have experience with poorly written lab instructions and will be using this prior knowledge in conjunction with our faculty consultant, Kyle Hanson, to prevent any potentially misleading directions.

Background Research on Induction Machine

Induction machines, also known as asynchronous machines, are one of the most widely used electrical motors in both domestic and industrial applications. About 50 percent of global power is consumed by electric machines, and over 90 percent of industrial machines are induction motors [2]. One of the main reasons it is so widely used is due to its high efficiency, which can achieve as high as 97 percent [3]. The high efficiency combined with low maintenance and self-starting properties makes the induction machine one of the most popular choices within the industry.

An induction machine comprises of two main components, the stationary stator and a rotating rotor. An exploded view of a common industrial squirrel cage type induction machine is shown in Figure 1. The main frame, typically made from cast iron, is used to house and protect the stator and rotor from damage as well as protect the user while operating. While sometimes not necessary, fans are also added to the machine to prevent the stator coils from overheating.

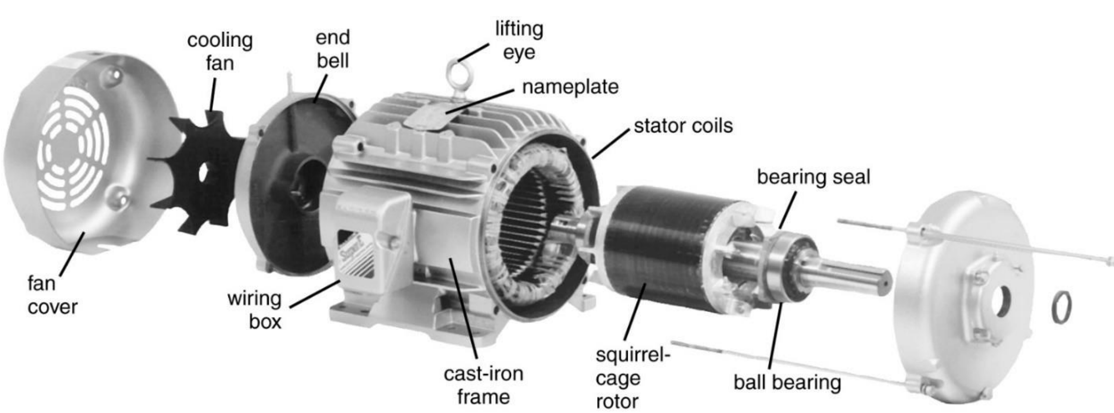


Figure 1. An exploded view of a squirrel-cage type induction motor [5].

A cross-sectional view of the stator is shown in Figure 2 and is derived from the design software. The stator of an induction machine is typically composed of stator windings and iron laminations. The copper windings in the stator of an AC machines are typically wound in a distributed fashion, meaning they are typically spread throughout the stator lamination [4]. Since an induction machine typically has three phases, the windings would have three individual input terminals. When the three-phase windings in the stator are connected to a three-phase power source, a rotating magnetic field is generated as the electromagnets interact. This rotating magnetic field induces a current in the rotor and generates torque in the rotor, creating a rotating motion. An example of a 4 pole, 12 slot machine motor and slot winding diagram are shown in Appendix A.

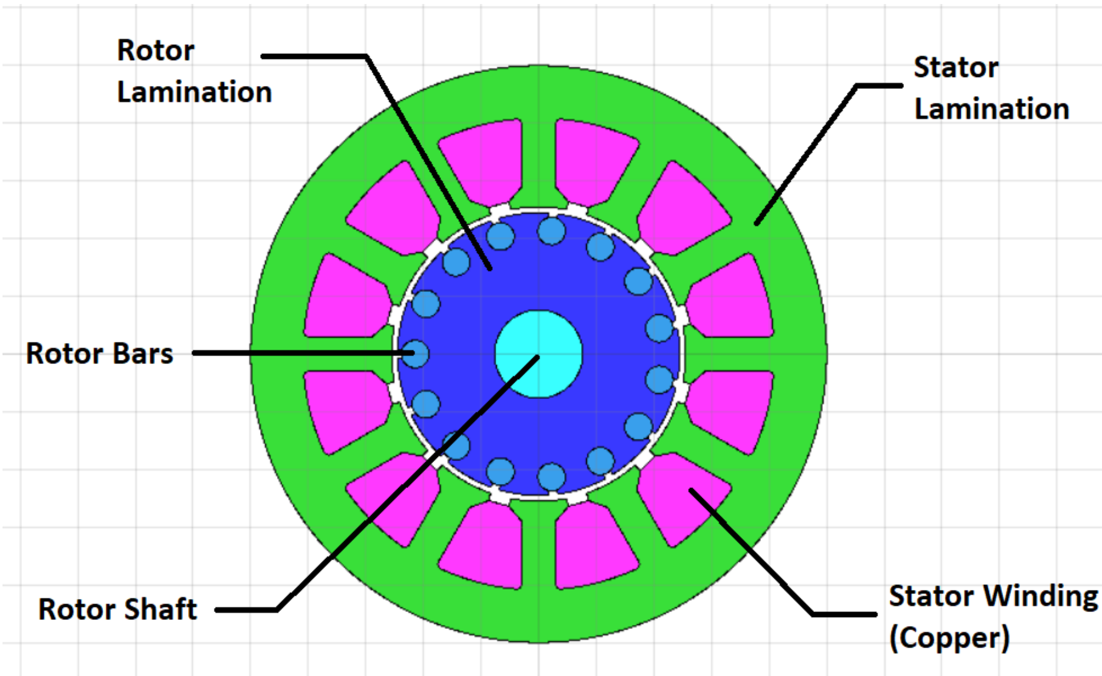


Figure 2. Cross-sectional view of a squirrel cage type induction machine stator and rotor.

One of the most common rotor designs for induction machine is the squirrel cage design. The construction of the squirrel cage rotor is shown in Figure 3.

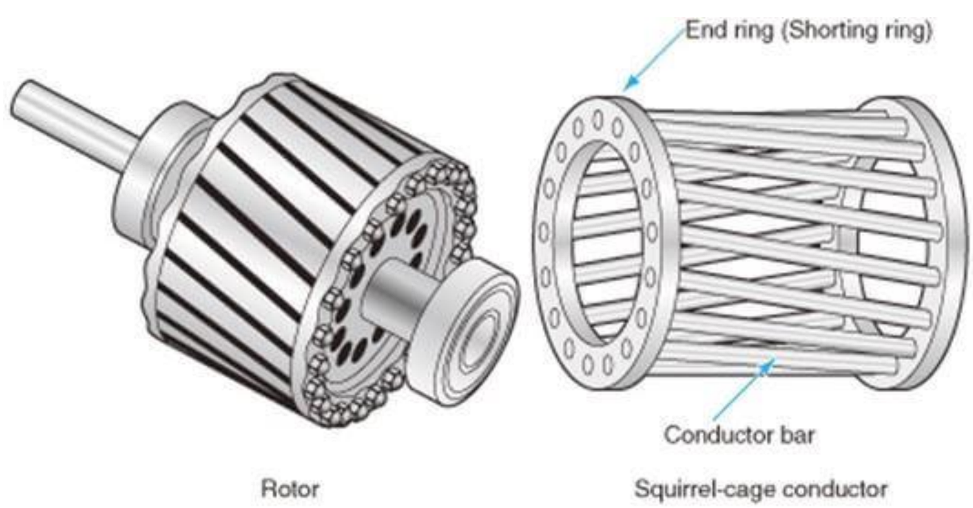


Figure 3. Construction of a squirrel-cage rotor [5].

The squirrel cage rotor design uses conducting bars (typically made from copper and/or aluminum) connected to a shorting ring on either end [4]. Within the cage, iron laminations are added to assist the flow of magnetic flux generated by the stator windings. A current is induced in the rotor bars when a rotating magnetic field is generated by the stator windings. The interactions between the induced current in the rotor and the rotating magnetic field in the stator allows the generation of torque in the squirrel cage rotor, causing a rotational motion. As seen above, the bars are skewed at an angle. This is to prevent cogging, which is a locking of the rotor upon startup that commonly occurs when there is an equal number of conductor bars and stator teeth [6]. Despite eliminating this, the motor may experience cogging in the form of running rough. The skew can help mitigate these adverse effects if properly implemented. For the scope of this project, skewing is ranked as a “nice to have” feature in later iterations but will not be included in the initial prototype.

Similar Solutions

The Grainger Prototype Lab had previously designed several brushed DC machines for classroom purposes. An example design is shown in Figure 4. This design was provided by our client and is currently being used in classes such as ECE 601 to provide students with hands-on experience.

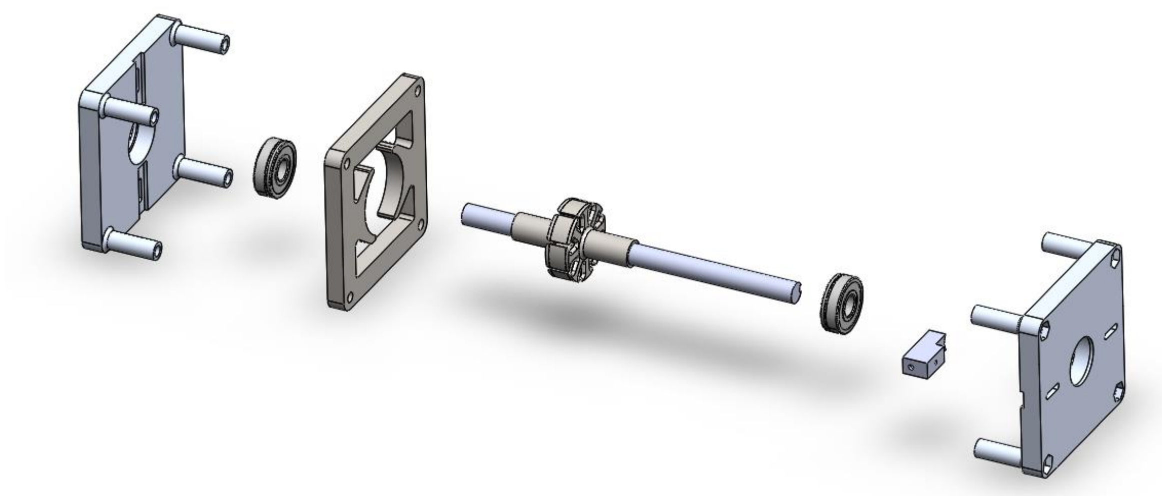


Figure 4. An exploded view of a brushed DC machine design that utilizes a 3D printed end plate.

This design provides a reference and a good starting point for the AC motor. The existence of the DC motor does not hinder the need for an AC motor because the two solutions are fundamentally different. Certain components, manufacturing techniques, and materials associated with the existing DC motor will be incorporated into the new design. The footprint of the AC motor will be relatively similar to that of the DC motor, and both will have to have the same dynamometer fixture compatibility for testing. There will be parallels in the design of new endplates, laminations, and axial components. The coil windings, stator, and rotor will reflect the fundamental differences between DC and AC motors, but the aforementioned similarities in auxiliary components will be very helpful in allowing a diversion of more resources towards the more complex components.

One can find similar induction motors in a plethora of different industries; however, these motors are normally suited for a specific application and are generally difficult to inspect and modify. They often have permanent or semi-permanent housings and are built using manufacturing techniques that cannot be rivaled by students for this project. Figure 1 illustrates how when fully assembled, industrial motors create a very robust, compact envelope that would have to be rigorously disassembled and likely redesigned for any other parameters to be used. Since students will be changing motor parameters, the “skeleton” of the design should not be very specialized, and the assembly should intuitively represent the factors and relationships that students will be studying. Similar solutions found in industry serve as design examples to reference for these reasons, but not as applicable solutions to the problem at hand. Though standards and patents were researched, none were found to be applicable for the general size and power output that this motor will feature, so everything will be designed from scratch. Industrial size induction motors will introduce standards and patents, but this is beyond the scope of research.

Apart from the motor design itself, there are many similar instruction manuals to that which will be included alongside the AC motor. Every industrial induction motor has an instruction manual of some capacity, but these manuals are often specific to the design and use at hand. Looking into fabrication manuals for similar individual components (e.g. laser cut part manual) as well as assembly instructions for entire motors will help the team write a comprehensive, robust, manual that translates well to what the students will likely encounter in industry.

Ideation and Decision Making

Since the act of students themselves fabricating the motor is imperative to fulfilling the main goal of the project, the team did not necessarily have a typical decision-making process. The project scope was defined by the client, leading to many parameters being pre-determined at the early stage of this project. The team investigated existing solutions; however, induction motor building kits are not very prevalent, and those found were either costly and/or included a higher percentage of prefabricated parts, decreasing student’s learning potential. Some parameters, such as number of poles and the use of single- or double-layer windings, are naturally set to a couple distinct factor levels. The main criteria to evaluate are manufacturability and cost. Specifically, the motor should be able to be built by students in approximately 10 weeks without prior fabrication experience. The total bill for each motor was set at about $100 or less. Manufacturability includes the ability to build using in-house tools and machines, ease of assembly, and repeatability/robustness of the design and process.

The first prototype utilized a 4 pole - single layer winding and a squirrel-cage rotor design. For further prototyping, the team created a decision matrix to identify the best alternative to move forward with. The design factors included are the number of poles, layers of stator winding, and rotor configuration. Generally, a 2-pole motor will not perform as well but would be easier to wind.

On the contrary, a 4-pole motor, taken as the industry standard, requires more work in winding but leads to a better motor that more accurately reflects what students may have to work with in the future. Lastly, the project objectives allow for a decision between two different rotor assembly configurations. The first prototype used copper bars, connected with copper end plates, to complete the rotor circuit. However, the client suggested that copper wires could be used as an alternative to simplify the manufacturing process and lower costs by eliminating the need to buy and cut copper rods. The importance of each factor was weighted in accordance with the client's idea of the project, and the evaluation of each alternative is shown in the design matrix in Appendix B.

Once the high-level motor design is set, there are several other parameters that impact the performance and quality of the design. Some of the important decisions made after the overall motor design are defined in the material, tolerancing, slot fill factor, output torque, and rotational speed sections, which are all discussed below. These factors are associated with performance and specificity than fundamentally meeting the project goals, which is why they were not included in the decision matrices. From this point in the design process, the use of JMAG became critical to the evaluation and further decision-making processes.

Materials

The stator and rotor laminations were constructed out of layers of lamination steel sheets. Steel is used as lamination for majority of the electric machines in the market due to its low cost and its high relative permeability. A material with high relative permeability allows the magnetic flux to travel through the laminations at a higher rate, which can lead to higher efficiency and better performance.

For the squirrel cage rotor, copper was selected as the material for the cage bars and endplates. Copper was chosen as it has a high electric conductivity. When current is being induced by the stator onto the rotor, the majority of the current will be induced within the copper instead of the steel lamination, which is important in achieving a higher efficiency. Alternatively, aluminum could also be used. However, an aluminum squirrel-cage requires a more complicated casting process, hence it is not being used in the first or any future prototypes.

Tolerancing

There were several areas where tolerancing decisions had to be made in the design phase. These included on the stator, rotor and copper end plates. In general, it is not an issue to have a conservative approach as the solder will help to hold everything in place. A judgement error regarding tolerancing was discovered in the rotor laminations in the first prototype and is discussed below.

Slot Fill Factor

The slot fill factor, also referred to as the slot fill percentage, is the ratio between the total electrical conductor a single stator lamination slot and the cross-sectional area of the slot in an induction motor. A simple illustration of this is shown in Figure 5.

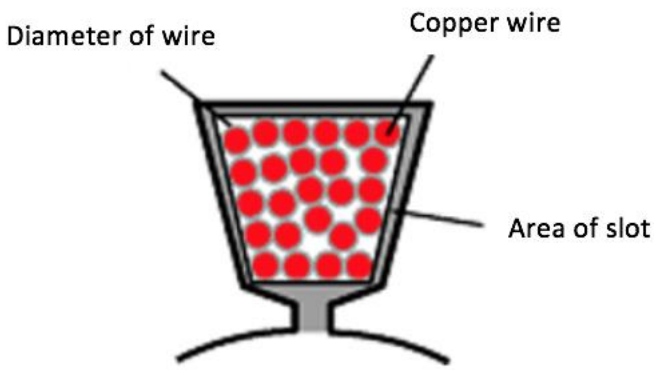


Figure 5. (Edited). Illustration of slot fill factor [8].

The slot fill factor is dependent upon the copper wire gauge and how tightly wound the assembler wraps the wire. It is inversely proportional to the amount of space between the copper wires, but it is proportional to the overall efficiency of the induction machine. The factor is dependent on the diameter of the wire, number of turns and the area of the slot. This relationship is shown in Equation 1.

$$Fill_{Factor} = \frac{2 \cdot \pi \cdot \left[\frac{d_{wire}}{2}\right]^2 \cdot N}{A_{slot}} \quad (1)$$

In Equation 1, d_{wire} is the diameter of the copper wire and N is the number of loops of copper wire. In order to increase the fill factor, manufacturers tend to use smaller gauge wire as it allows more loops to pass through the lamination slot and leads to a higher efficiency motor. Some advanced motors would incorporate rectangular wire in favor of round wire to achieve even greater fill factors. Efficiency as a function of slot fill factor and rotational speed can be seen in Figure 6.

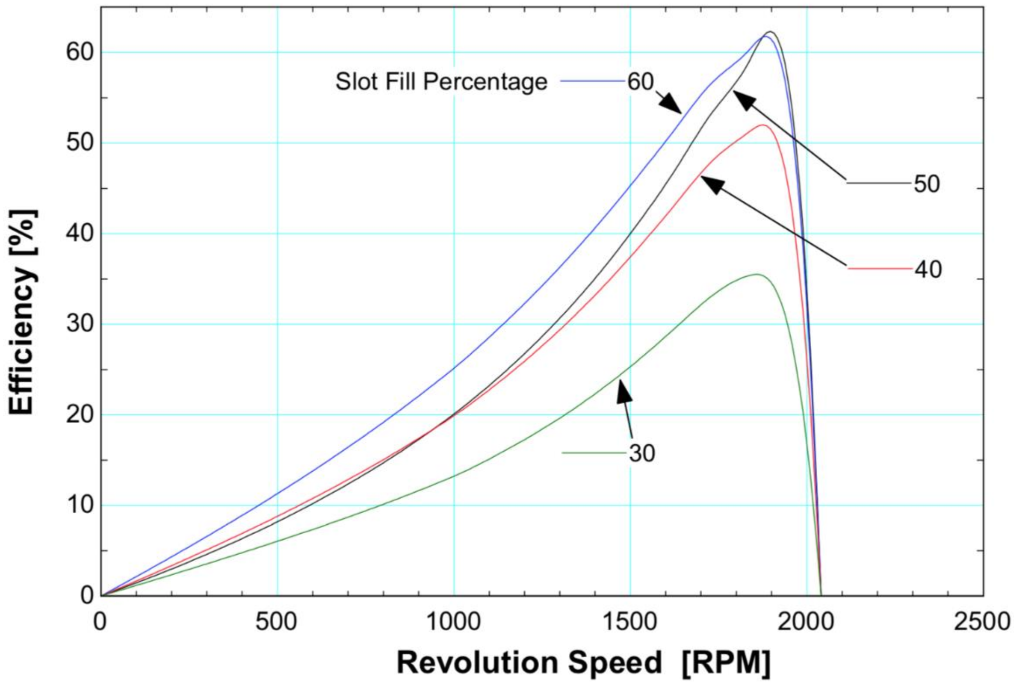


Figure 6. Machine efficiency as a function of the slot fill percentage and speed.

This data was analytically collected using JMAG Express. Using the slot fill percentage input value, different values were tested. In this project's designs, a typical slot fill factor may fall in the 40-50% range. This was the range also specified by the client. As the slot fill factor increases, the increase in efficiency becomes less significant. A value of 45% was achieved in the first prototype.

Torque and Rotational Speed

When designing an induction machine, designers typically focus on the relationship between torque and rotational speed. The intent of this project is more so to focus on manufacturability, but analyzing data is still important in conceptualizing how well the motor functions. A torque vs. RPM curve for our 4-pole machine is shown in Figure 7.

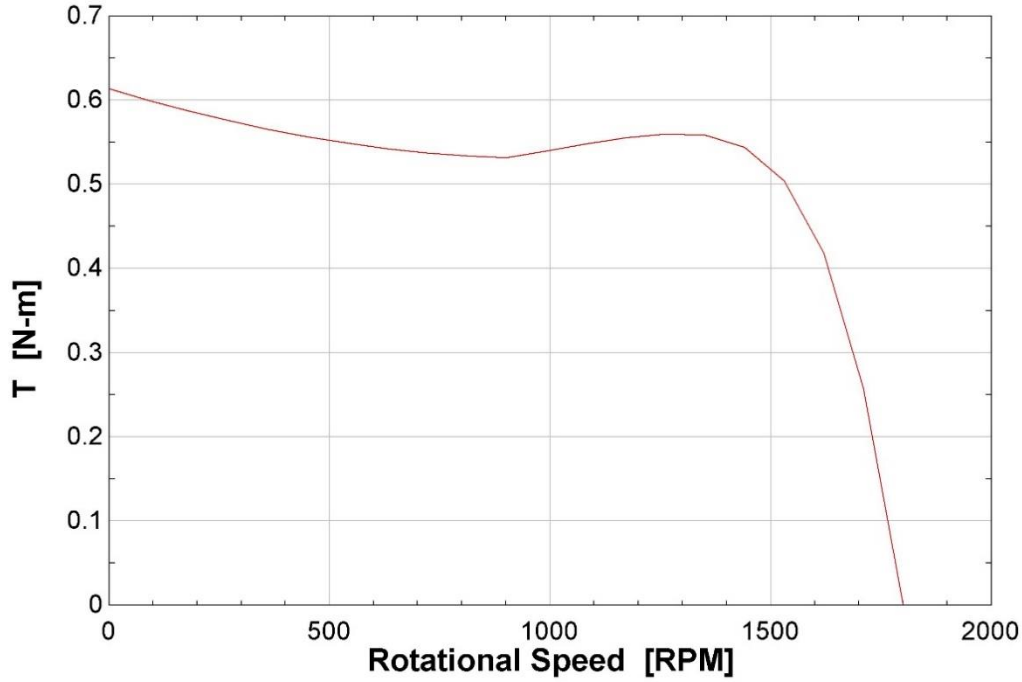


Figure 7. Torque vs RPM graph. Result obtained from JMAG Express simulation.

Based on Figure 7, the simulation result shows that the machine design has a high starting torque of about 0.6 N-m at stall condition and a synchronous speed of 1800 RPM. The synchronous speed describes the rotational speed of the machine under no load condition and is a pole and frequency specific number. When the machine reaches the synchronous speed, the rotor of the machine rotates at the rate as the rotating magnetic field generated by the stator winding. Since they are rotating at the same rate, there is no change is magnetic field in accordance with Faraday's Law. Hence, no current is induced in the rotor and no torque is generated (this can be seen in the figure above- at synchronous speed of 1800 RPM, the torque value is 0 N-m).

Prototyping

As soon as the specifications were decided upon as outlined in the ideation and decision-making section of this report, the first step was to formulate a plan of action. Using a Gantt Chart and numerous team meetings, a scheduled trajectory leading to the end goal of a spinning prototype was created. The first step was the creation of detailed CAD models, the second was to be deciding upon parts and placing the order, the third was fabrication, and the last was testing.

CAD Generation

CAD models are useful in many respects. They give both the engineer and the client a visual on what is to be built to ensure that there are no mismatched expectations, allow for a final check of feasibility of manufacturing, and are also necessary for many modern-day manufacturing methods such as CNC laser cutting, CNC water jetting, and 3D printing. The team generated a CAD assembly in SolidWorks for the entire induction motor before beginning fabrication. The prototype can be thought of as two different larger assemblies, stator/housing, and rod/rotor. The fully assembled model as well as the exploded view of these two subsets can be seen in Figure 8 below. Future prototypes will utilize the current SolidWorks file; however, each prototype will have its own file.

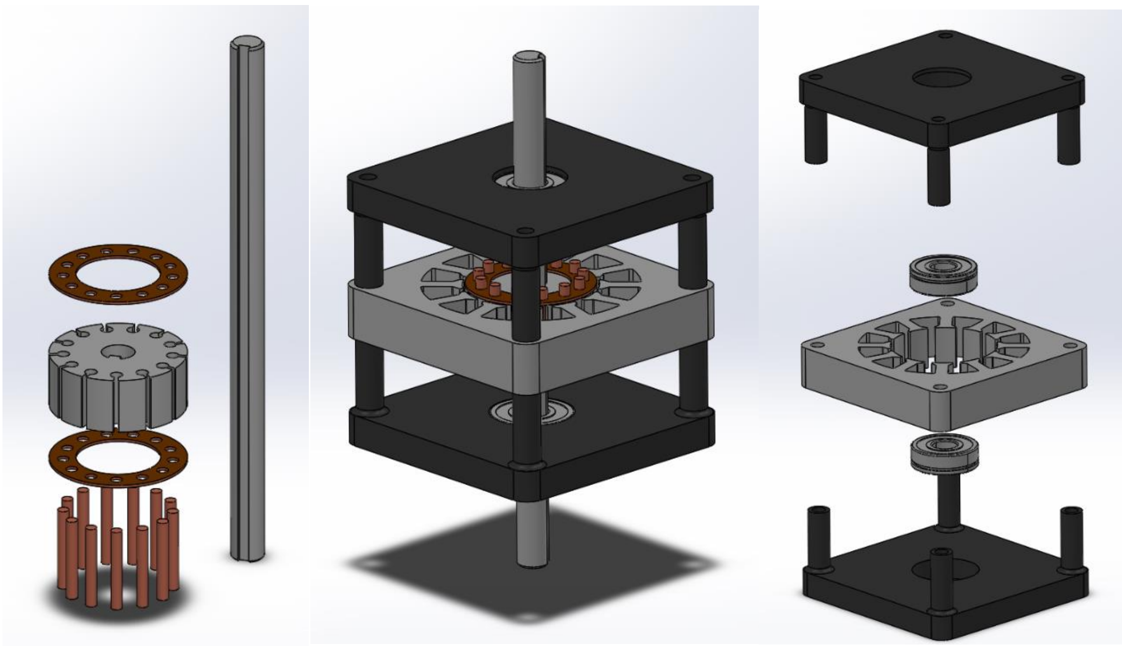


Figure 8. Full Prototype Assembly.

All dimensions were decided upon by outputs from JMAG Express or directly from the manufacture's website in the case of the bearings and keyed shaft. An important decision regarding dimensioning made during the CAD model generation stage was introducing the concept of adding clearance. While the housing, rod, and bearings had already been tolerance due to being pulled directly from a previously built DC machine, the rotor and copper end plates had to have clearance added to ensure for easy assembly post fabrication. The places which clearance was added as well as how much was added can be seen in Figure 9 and Table 2 below. While addition of these clearances may seem like a minor detail, it heavily affected our ideas for future prototypes. For more details, see the Future Iterations section below.

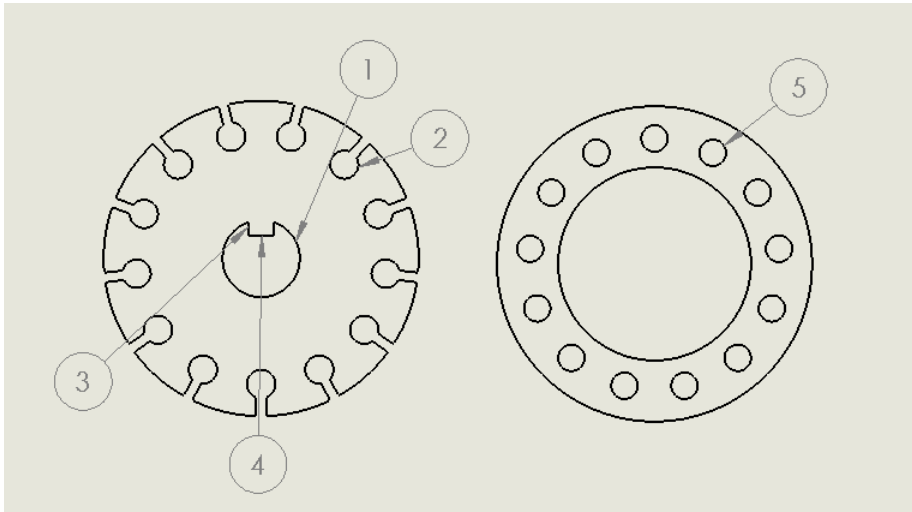


Figure 9. Clearance Addition Locations

Table 2. Clearance Values.

Location	Zero Clearance Size [mm]	Initial Clearance Added [mm]	Manufacturing Method
1	4	0.16	Laser Cut
2	12	0.02	Laser Cut
3	2.5	0.34	Laser Cut
4	4	0	Laser Cut
5	4	0.11	Water Jet

There were a few decisions that went into determining what kind of clearance would be used for each dimension. The first consideration was tolerance of the machine. While both machines are highly accurate, there is still some variation between cuts as admitted by the manufacturer. While testing and working with the machine overtime gives by far the best idea of how much clearance should be added, knowledge of these machine tolerances gave a starting point for determining how much clearance should be added. The second consideration was assembly process. It was determined that all laminations of the rotor (on the left in Figure 9) would be placed on the shaft to help with both stability and orientation during the assembly process after which the copper bars would be pushed into the smaller holes. The copper end plates would then be placed on top. Because of this intended assembly process, the key for the shaft (Location 4) was given a smaller clearance when contrasted with the copper bars (Location 2) due to the ease of being able to stack all laminations one at a time. Likewise, location 5 also has a smaller clearance than Location 2. The combinations of these two considerations produced estimated clearances needed, and coupled with dimensions from JMAG Express, the CAD models were fully dimensioned.

Part Ordering

With the CAD model as a base, parts were found and purchased almost exclusively from McMaster-Carr, which was found to be the best supplier for the project purpose due to specialization in low quantity and non-conventional sizes (particularly the 4 [mm] rod). While this is not ideal for cost minimization when looking toward a somewhat mass-produced end product, it still adheres to the $100/motor budget set in the design specifications and can be improved upon in the future as the design is updated. Fasteners were purchased from Fastenal, which is the supplier of choice of the client. All parts were purchased through the WEMPEC system and were thus funded by the client rather than the ME 351 funds. Many motor components were also provided by the lab at no cost to the team, however the team will be accounting for these costs in the future. The budget history for purchased parts is shown below in Table 3.

Table 3. First Prototype Cost Analysis.

Bill of Materials							
	Induction Motor Team					Design Iteration:	1
Item	**Description**	**Material**	**Source**	**Quantity**	**Measurement**	**Unit Price**	**Total Price**
In House Parts							
Motor Housing	Motor Housing	Polymer	3D Printer - In Lab	1	100mm x 100mm	$30.00	$30.00
Windings	18 AWG Wire	Copper	Stocked In House	1	tbd	$15.00	$15.00
Stator Core	Stator core comprised of lamination stack	26ga Steel	Laser Cutter - In Lab	1	20mm OVL th	$0.00	$0.00
Rotor Core	Rotor core comprised of lamination stack	26ga Steel	Laser Cutter - In Lab	1	20mm OVL th	$0.00	$0.00
						Subtotal:	**$45.00**
Purchased Parts							
Bearings	6201-2Z Shielded Ball Bearing	Steel	McMaster-Carr [5972K327]	2	12mm ID x 32mm OD	$5.55	$11.10
Shaft	Keyed Rotary Shaft	304 SS	McMaster-Carr [7398K215]	1	200mm L x 4mm OD x 3mm D	$11.55	$11.55
Rotor Bars	Copper rods, 30mm in length. 13 needed for rotor (390mm)	110 Cu	McMaster-Carr [8966K93]	0.5	4mm OD x 1m L	$12.62	$6.31
Rotor End Plates	End plates enclose rotor components (1mm th x 49mm OD, ~9 per raw stock unit)	110 Cu	McMaster-Carr [8963K179]	0.25	0.04" th x 6"sq	$18.65	$4.66
Fasteners	M6-1x130mm hex cap screw + M6-1 wing nut [qty = 1 pair]	Steel	Fastenal Bolts:[11113709] Nuts:[90673]	4	Bolts: M6-1x130mm Nuts: M6-1	$2.40	$9.60
						Subtotal:	**$43.22**
						Total:	**$88.22**

Fabrication

The fabrication process began as soon as the materials arrived. The endplates were 3D printed with the WEMPEC Markforged ONYX PRO printer, the steel for the rotor and stator laminations was cut from the WEMPEC FabLight 4500 laser cutter, the stock copper rod was cut into pieces with a band saw, and the copper end plates were turned over to the UW-Madison Makerspace for water jetting. Upon attempting to assemble the fabricated parts for the first time, it became very clear that something did not go as planned during the cutting of the rotor laminations. As can be seen in the image below, laminations were not cut as identically as hoped, leading to the radial holes to misalign by a critical amount.

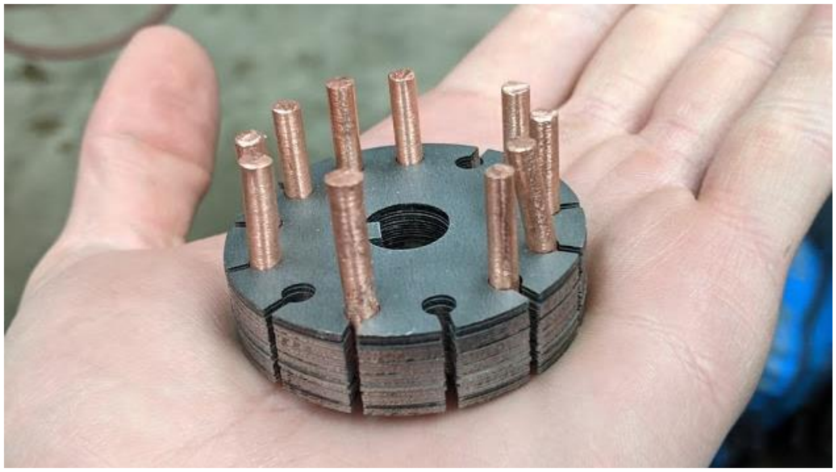


Figure 10. Initial Failed Rotor Lamination Cut Quality.

The team decided to try to make the fit work regardless of the tight fit and sanded roughly 0.15 [mm] off the diameter of the copper rods, which allowed some to maintain enough clearance to fit in the rotor laminations. As more bars were added, further restricting possible clearance, a press was used in a final attempt to assemble the pieces. It became apparent that something would have to be done to address the issue for future iterations regardless, and the team learned that the absence of tab features on the rotor lamination led to higher disparity during the cutting process. Additional tolerance was also allotted to the laminations to ensure the copper bars cut fit through all 43 sheets. The rotor laminations were recut, and immediate improvement was observed as the copper bars fit into the rotor.

With the rotor assembled, the copper bars needed to be soldered to the copper end plate. With a low powered soldering machine, the soldering took approximately 3 hours. This is not optimal for a machine that is supposed to be easily assembled but will be considered as a potential area for improvement in future prototypes.

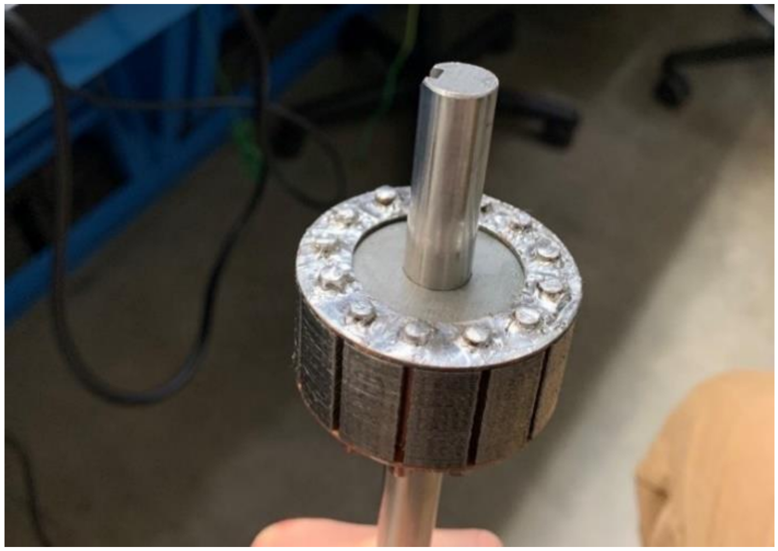


Figure 11. Rotor Squirrel-cage endplate soldered to rotor bars.

The stator, housing, and windings were assembled after the rotor was complete. The winding parameters were prescribed by the decided upon JMAG express design as seen in the Ideation and Decision-Making section of this report. Windings were wound using a small hand crank winding machine in the WEMPEC lab. All windings were 24 AWG wire and were set as bundles into the stator as seen in Figure 12 below. With the windings set in the stator, the wires were connected as seen in Appendix Figure A-2, and the end windings were connected in a 'Y' connection. Three inputs were established to power the 3 pole pairs of the motor and were soldered to the three bananas plug inputs seen in the right image below. This would allow for easy input to the 3-phase power supply that is to be used for powering of the machine for initial testing. These banana plugs are displayed in Figure 13.

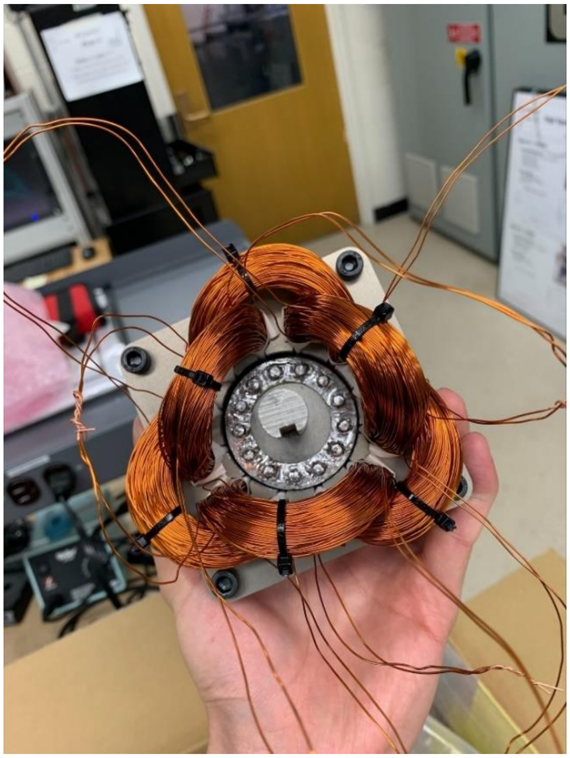


Figure 12. Windings Set in Stator.

Figure 13. Banana Plug Ends of Windings

With the stator completely assembled, the rotor, housing, and stator were easily assembled to complete the initial prototype observed in Figure 14.

Figure 14. Fully Assembled Initial Prototype.

Analysis

The last step in the prototyping process was to conduct three tests. These include a HIPOT test, a phase resistance test, and a test to ensure that the motor spins when hooked up to the three-phase power supply. The primary focus of these tests is to make sure the motor spins, but it also ensures the safety of students in the lab.

The first test was a HIPOT test, which in the case of this low voltage motor was adequately performed using a multimeter set to a continuity test. Each test passed ensuring that all components had been successfully electrically insulated from each other by touching each winding and the stator with the multimeter to ensure that there are no shorts to the stator and each winding to the other windings.

The phase resistance and spin tests were run simultaneously. With the machine hooked up to a three-phase power supply, the voltage was set at 5 V_{rms} and frequency of 15 Hz. With this set-up as well as with many different configurations of the voltage and frequency the motor spun correctly on the first try. The inputs and outputs can be seen in the Figure 15.

Figure 15. Testing first prototype using the 3-phase power supply.

From the output parameters of the machine, a phase resistance test can be deduced. The phase currents and the voltages can be seen displayed. By comparing the currents, phase ‘A’ has a lower impedance when contrasted with the other two, but not so significantly as to affect the performance. This is most likely due to an error in the number of windings or an unequal size of the windings but is acceptable as a pass for the phase resistance test. This slight discrepancy will be looked at in further detail before the fabrication of the second prototype.

Table 4 shows the rotational speed of the shaft under different voltages and frequencies observed while hooked up to the 3-phase power supply.

Table 4. RPM vs varying voltage and frequency

Voltage (V)	Frequency (Hz)	Speed (RPM)
5	15	367
8	15	410
8	30	789
15	30	862
15	35	991
15	40	1132
15	60	1744

The theoretical synchronous speed of the 4-pole induction machine is 1800 RPM at a 60 Hz frequency. Based on result from Table 4, the slip at synchronous condition is approximately 3.11%.

Future Iterations

As the first semester of working on this project concludes, a foundation for future ideas for optimization is crucial to ensuring that the project reaches its full potential. Two primary categories have been thought of to help reach this goal: improve manufacturability and decrease costs.

Improving Manufacturability

Manufacturability, as thoroughly discussed in the ideation and decision-making section of this report, is one of the most important parameters of the build. As seen in the prototyping section of this report, the prototype motor is not practical for a simplistic and efficient student build. Client feedback and experiences with fabrication led to ideas for future iterations that would lead to easier manufacturability for the student.

The client had two main focusses for improving manufacturability – improving the squirrel cage design and reducing the space taken up by windings. The squirrel cage design improvement could reduce in lab time by eliminating soldering. Ideas for this improvement are substituting the copper bars for aluminum fasteners or copper wiring. Aluminum fasteners could easily be pushed through the rotor and clamped onto the copper end plate. This eliminates the need for solder. Using low gauge wire wound through the rotor in a pattern that connected all the slots where the copper rods currently are could eliminate the need for soldering as well as the need for copper end plates. Another client focus was improving the windings because they extruded well outside the housing in the first prototype and made it difficult to set in the stator. The client has recommended using higher gauge wire with more loops to make setting each loop set in more manageable or a reduction in the overall number of loops. While decreasing the number of loops would cause a hit on performance, because the goal of this project is to simply have a motor that spins. This would not jeopardize any outcome objectives.

Improving the rotor and the winding designs would satisfy client feedback, but the team also wishes to implement a few other ideas to improve manufacturability that were discovered during fabrication. These include allocating a larger rotor bar clearance and implementing a winding jig for students. The first stems from the problem that the team encountered in the prototyping section where at first the copper bars did not fit through the rotor laminations. While the clearance was improved in the second cutting of the laminations, it was overcompensated for leaving a loose fit between the bars and the stator, making soldering very difficult. While it was mentioned previously that the rotor can be improved to eliminate soldering all together, this may not be an issue. Improving the clearance to compensate for the bars will be crucial if the copper bar approach is used again. The second improvement is adding a custom winding jig. As discussed in the prototyping section, the team used a hand winding machine in the WEMPEC LAB to make all the windings. While it was simple to use and did not take much time, there is only one available, making it likely to cause a bottle neck in a potentially large classroom. The effects would be compounded by the fact that winding is one of the more time-consuming processes of the build. A 3D printed part could be made for each student to help aid in the winding process, or a common household item could also be found and recommended to the student. This will be especially useful if the number of windings is able to be reduced to a number that could be easily kept track of in a student's head.

Decrease Costs

Cost is the second component of future iteration. Since the first prototype already came in under the specified budget, decreasing costs is of a lower priority than manufacturability. The first prototype used comparatively expensive components from McMaster-Carr to comply with our first set of design specifications. The potential for cost reduction is very great and can be cut in a few key areas. By implementing the rotor and winding design ideas outlined in the section above, costs would drop. Eliminating relatively expensive copper stock, reducing solder use, and reducing the amount or winding wire needed would also reduce costs. A transition could also be made from metric to imperial dimensions. This would make pieces like shafts, bearings, fasteners, and copper bars (if needed) easier to find from different vendors, and likely cheaper as well. Another way to potentially cut costs would be to utilize bulk purchasing options. As the prospective class will likely have more than ten students enrolled, bulk purchasing could greatly reduce the cost of each machine. Certain parts from the build are more standard than others, but the parts most likely to be made custom for different groups are conveniently the parts made in house. The team can purchase larger quantities of fasteners, raw stock, and bearings specifically to dramatically decrease the per-unit cost. These are current cost reduction options; it is expected that others may appear as more fabrication is completed.

Decision Matrices

Some of the areas of improvement listed above will resolve to relatively clear choices. Once costs are cut in key areas and a different winding configuration is reached, the winding jig can be added (budget allowing) and its effects on manufacturability and cost can be evaluated. Purchasing bulk materials for the student motors is also a decision that does not require much deliberation. Others, such as a new rotor cage design or altering the stator windings, require further consideration to decide whether the given change is advantageous. Design matrices for certain future iteration parameters are shown in Appendix B. For the overall design, the baseline was set as a motor building kit available on the market [7], even though such an option was not going to be very seriously looked at due to the project specifications.

Appendix A:
Motor and slot diagram of a 4 Pole – 12 Slot Induction machine

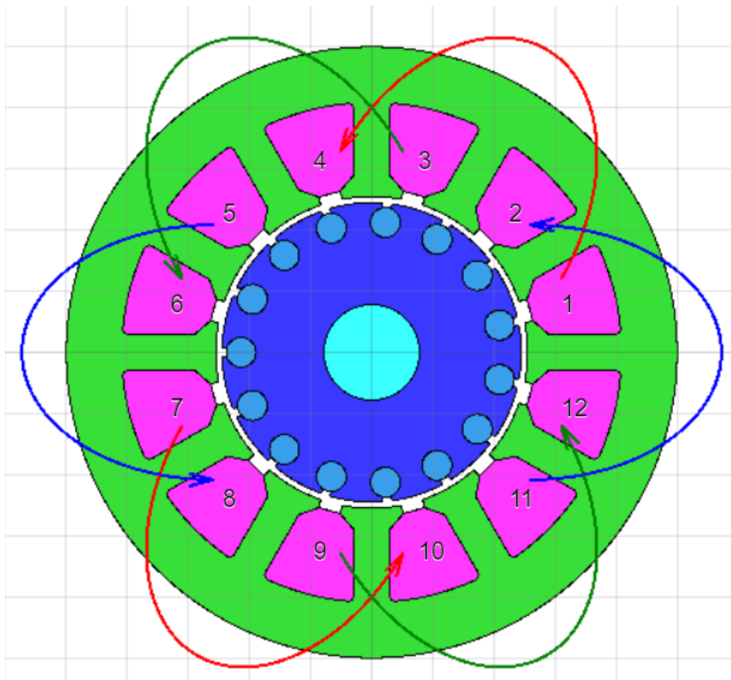


Figure A-1. Motor diagram of a 4 Pole – 12 Slot induction machine.

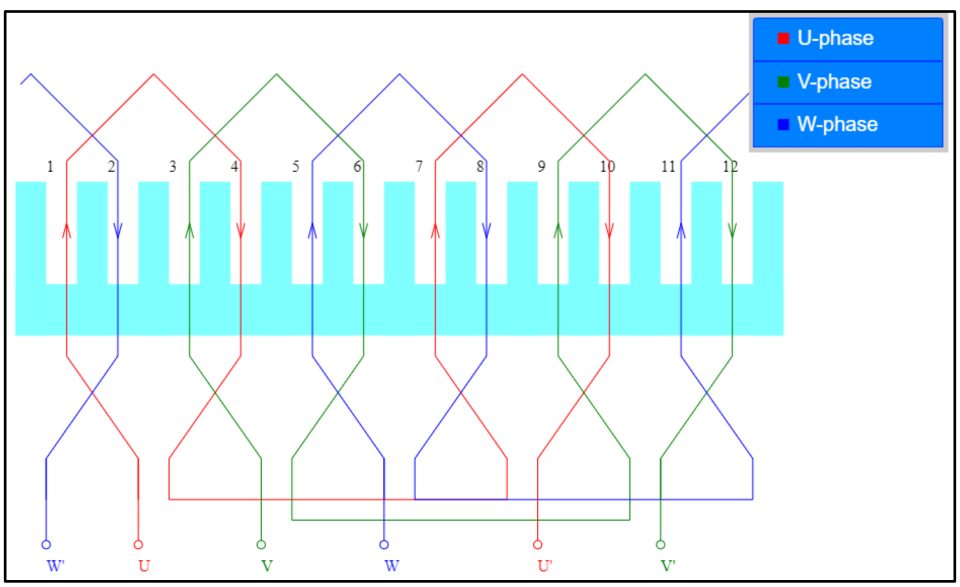


Figure A-2. Slot diagram of a 4 Pole – 12 Slot induction machine.

Appendix B:
Decision matrices for design parameter specification and ideation.

Table B-1. Decision Matrix for Overarching Motor Characteristics.

Design Spec:	Levels:	Baseline - Kit	Design A	Design B	Design C
Winding Layer Type	Single Double	Single or Double	**Single**	Double	Single
Number of Poles	2 [3600 rpm] 4 [1800rpm]	4	**4**	2	2
Consideration:	**Relative Importance:**	**Baseline - Kit**	**Design A**	**Design B**	**Design C**
Manufacturability	30	1	**0.25**	0.3	0.3
Cost	25	0.1	**0.8**	0.8	0.8
Learning Potential	35	0.25	**0.95**	0.9	0.9
Efficiency	10	1	**0.8**	0.6	0.65
Rating (Highest Most Favorable)	(/100)	51.25	**68.75**	66.5	67
*Design A (in bold) was used for the first prototype.					

Table B-2. Decision Matrix for Squirrel Cage Rotor Design.

Design Spec:	Levels:	Baseline	Design A	Design B
Squirrel Cage Design	1) Bars + End Plates 2) Continuous Wire 3) Alum. Fasteners	1	2	3
Consideration:	**Relative Importance:**	**Baseline**	**Design A**	**Design B**
Manufacturability	30	0.25	0.5	0.35
Cost	25	0.8	0.95	0.85
Learning Potential	35	0.95	0.95	0.95
Efficiency	10	0.8	0.7	0.7
Rating (Highest Most Favorable)	(/100)	68.75	79	72
*Baseline is First Prototype Built				

Table B-3. Decision Matrix for Stator Winding Configuration.

Design Spec:	Levels:	Baseline	Design A	Design B
Stator Winding Configuration	1) 24 AWG | N Loops 2) 24 AWG | <N Loops 3) >24 AWG | >N Loops	1	2	3
Consideration:	**Relative Importance:**	**Baseline**	**Design A**	**Design B**
Manufacturability	30	0.25	0.6	0.5
Cost	25	0.8	0.9	0.9
Learning Potential	35	0.95	0.95	0.95
Efficiency	10	0.8	0.6	0.6
Rating (Highest Most Favorable)	(/100)	68.75	79.75	76.75
*Baseline is First Prototype Built. N=Loops in First Prototype				

References

[1] D. W. Knight, L. E. Carlson, and J. F. Sullivan, "Staying in engineering: Impact of a hands-on, team-based, first-year projects course on student retention," ASEE Annu. Conf. Proc., pp. 10037–10047, 2003.

[2] M. Kostic, "Effects of Voltage Quality on Induction Motors' Efficient Energy Usage," *IntechOpen*, 14-Nov-2012. [Online]. Available: https://www.intechopen.com/books/induction-motors-modelling-and-control/effects-of-voltage-quality-on-induction-motors-efficient-energy-usage. [Accessed: 27-Feb-2021].

[3] U.S. Department of Energy: Industrial Technologies Program, "Improving Motor and Drive System Performance :," *Ind. Technol. Progr.*, pp. 3, 45, 46, 2008.

[4] J. D. Edwards and J. D. Edwards, "Introduction to AC Machines," *Electr. Mach. Drives*, pp. 102–129, 1991, doi: 10.1007/978-1-349-21313-9_4.

[5] "Operation of ship's Induction Motors," *Electro*, 25-Jan-2019. [Online]. Available: https://electrotechnical-officer.com/operation-of-ships-induction-motors/. [Accessed: 28-Feb-2021].

[6] "What is Cogging in Induction Motor? - Magnetic Locking," *Circuit Globe*, Jan. 29, 2016. (accessed Feb. 26, 2021)

[7] "Motor Winding Kit," *Festo.* https://labvolt.festo.com/solutions/6_electricity_and_new_energy/59-8022-00_motor_winding_kit (Accessed: March 9, 2021).

[8] S. Meier, "Slot fill factor," *Emetor*. [Online]. Available: https://www.emetor.com/glossary/slot-fill-factor/ (Accessed: March 19, 2021).

Midyear Report Rubric

Faculty Consultant Signature:	Grade:
Team Name:	

Instructions

Mark the box for each item in the rubric and add positive and/or constructive comments for each section if desired.

Technical Communication

	Strongly Disagree	Disagree	Agree	Strongly Agree	Comments
structure					
The document organization is logical, mapped for the reader, and enhances the readability.					
style					
The writing style is efficient, clear, precise, and lends credibility to the authors.					
mechanics					
Document is proofread and readable. References are cited. Graphics and equations effectively communicate relevant information.					

Content

	Strongly Disagree	Disagree	Agree	Strongly Agree	Comments
research					
Excellent research that convincingly supports decisions.					
Relevant standards are applied to the project. An acknowledgment and justification are provided if no standards apply.					
Sources are varied, well-documented, and credible.					
calculations					
Clearly evident that engineering calculations have guided design decisions.					
Discussion of calculations in text are clear and memorable, have an appropriate level of detail, and enhance the readers understanding.					
Appropriate documentation of calculations in appendix.					

client					
Evident in all aspects that client interaction is driving the design process.					
Clients and relevant stakeholders are clearly defined.					
Evident that client interaction is ongoing and that future interaction is planned					

design specification					
Client requirements are clearly translated into engineering requirements and the appendix includes a full design specification.					
Competing products and/or solutions are clearly mined for and translated into engineering requirements (if applicable).					
Thorough work done to clearly communicate the essential aspects of a more comprehensive design specification.					

ideation and decision matrices					
Clearly evident that multiple concepts have been considered.					
Concepts are evaluated rigorously and with client requirements in mind.					
Thorough work done to clearly communicate the essential aspects of the evaluation process.					

prototyping					
Prototyping is directlty connected to the design specification, and therefore the client.					
Client feedback from prototypes is directly impacting design decisions.					

Midyear Report Rubric

Instructions
Mark the box for each item in the rubric and add positive and/or constructive comments for each section if desired.

Faculty Consultant Signature:

Grade: 95

Team Name: Induction Motor

Technical Communication	Strongly Disagree	Disagree	Agree	Strongly Agree	Comments
structure					
The document organization is logical, mapped for the reader, and enhances the readability.				X	
style					Good sources where applicable
The writing style is efficient, clear, precise, and lends credibility to the authors.				X	
mechanics					
Document is proofread and readable. References are cited. Graphics and equations effectively communicate relevant information.				X	
Content					
research					No standards apply for motors of this size - more applicable for motors in industry (page 7)
Excellent research that convincingly supports decisions.			X		
Relevant standards are applied to the project. An acknowledgment and justification are provided if no standards apply.				X	
Sources are varied, well-documented, and credible.				X	
calculations					Calculations not a primary focus in meeting client needs. Manufacturability is more important than performance. Covered in Ideation + Decision Making
Clearly evident that engineering calculations have guided design decisions.				X	
Discussion of calculations in text are clear and memorable, have an appropriate level of detail, and enhance the readers understanding.				X	
Appropriate documentation of calculations in appendix.				X	

client					
Evident in all aspects that client interaction is driving the design process.				X	Client needs were utmost priority in the design process
Clients and relevant stakeholders are clearly defined.				X	
Evident that client interaction is ongoing and that future interaction is planned				X	
design specification					
Client requirements are clearly translated into engineering requirements and the appendix includes a full design specification.				X	A design matrix was implemented per client request
Competing products and/or solutions are clearly mined for and translated into engineering requirements (if applicable).			X		
Thorough work done to clearly communicate the essential aspects of a more comprehensive design specification.				X	
ideation and decision matrices					
Clearly evident that multiple concepts have been considered.				X	Building 3-5 prototypes, the team will begin to expand our design considerations
Concepts are evaluated rigorously and with client requirements in mind.				X	
Thorough work done to clearly communicate the essential aspects of the evaluation process.				X	
prototyping					
Prototyping is directlty connected to the design specification, and therefore the client.				X	The team has received suggestions regarding future design consideratio and will consider those going forward
Client feedback from prototypes is directly impacting design decisions.				X	